THE NIKE ELECTRON BEAM-PUMPED KrF LASER AMPLIFIERS

J.D. Sethian, C.J. Pawley, S.P. Obenschain, K.A. Gerber, V. Serlin, and C. Sullivan
Code 6730, Plasma Physics Division, Naval Research Laboratory, Washington, D.C.

T. Lehecka
Science Applications International Corporation, McLean, VA.

W. D. Webster
East Coast Engineering, Alexandria, VA

I.D. Smith, P.A. Corcoran and R.A. Altes
Pulse Sciences, Inc. San Leandro, CA

Abstract

Nike is a recently completed multi kilojoule krypton fluoride (KrF) laser that has been built to study the physics of direct drive inertial confinement fusion. The two final amplifiers of the Nike Laser are both electron beam pumped systems. The smaller of the two has a 20 cm x 20 cm aperture and produces an output laser beam energy in excess of 100 Joules. This *20 cm Amplifier* uses a single 12 kJ Marx generator to produce two 300 kV, 75 kA, 140 nsec flat top electron beams that are injected into opposite sides of the laser cell. The larger amplifier in Nike has a 60 cm x 60 cm aperture, and amplifies the laser beam up to 5 kJ. This *60 cm Amplifier* has two independent electron beam systems, with each side powered by a 170 kJ Marx Generator that produces a 670 kV, 540 kA, 240 nsec flat top electron beam. Both amplifiers are complete, fully integrated into the laser, and meet the Nike system requirements. Laser-target experiments have begun.

Introduction

Nike is a large angularly multiplexed Krypton-Fluoride (KrF) laser that has recently been completed at the Naval Research Laboratory. The laser will deliver up to 2.2 kJ of 248 nm light onto a planar target (plus another 800 J in a backlighter), with intensities of approximately 2×10^{14} W/cm^2 in a 4 nsec pulse. Nike has been built to explore the technical and physics issues of direct drive laser fusion[1]. It uses spatially and temporally incoherent light to reduce the low-mode intensity nonuniformities to less than 2% in the target focal plane[2]. These nonuniformities are the maximum thought to be allowable for high gain ICF targets. The Nike laser consists of a commercial oscillator/amplifier front end, an array of discharge amplifiers, two electron beam pumped amplifiers (one with a 20 cm x 20 cm aperture, the other with a 60 cm × 60 cm aperture) and the optics required to relay, encode, and decode the beam.

The electron beams excite a krypton-fluoride gas mixture inside a laser cell. Because the decay time for excited KrF is only a few nsec, the energy must be extracted continually during the pumping phase. This limits the extracted laser power to the rate at which energy can be deposited into the amplifier, and in turn results in a mismatch of timescales: While high

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14. ABSTRACT
Nike is a recently completed multi kilojoule krypton fluoride (KrF) laser that has been built to study the physics of direct drive inertial confinement fusion. The two final amplifiers of the Nike Laser are both electron beam pumped systems. The smaller of the two has a 20 em x 20 em aperture and produces an output laser beam energy in excess of 1 00 Joules. This 20 em Amplifier uses a single 12 kJ Marx generator to produce two 300 kV, 75 kA, 140 nsec flat top electron beams that are injected into opposite sides of the laser cell. The larger amplifier in Nike has a 60 em x 60 em aperture, and amplifies the laser beam up to 5 kJ. This 60 em Amplifier has two independent electron beam systems, with each side powered by a 170 kJ Marx Generator that produces a 670 kV, 540 kA, 240 nsec flat top electron beam. Both amplifiers are complete, fully integrated into the laser, and meet the Nike system requirements. Laser-target experiments have begun.

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energy electron beam systems have output pulse times of a few hundred nsec, the physics of ICF require pulses of only a few nsec. These timescales are matched using angular multiplexing[3]. The laser starts with a single pulse that is the desired 4 nsec long. This pulse is repeatedly divided and amplified to obtain a train of pulses that are each 4 nsec long. Throughout this process, the individual pulses are deflected so that each pulse passes sequentially through the electron beam pumped amplifiers at a slightly different angle. Thus the amplifiers effectively drive one continuous pulse. (There are 28 pulses that are passed through the 20 cm amplifier, and 56 through the 60 cm amplifier.) After amplification, the individual pulses are delayed and steered the appropriate amount so that they all arrive simultaneously on target to create a single, 4 nsec long, high power pulse.

Both of the two final amplifiers are double sided e-beam systems. The electron beams are formed in a rectangular cross-section field emission diode and transported into the laser cell from opposite sides and in a direction perpendicular to the laser beam. Magnetic fields are used to guide the beams and prevent self-pinching. Both Nike amplifiers have met the three principal requirements for the laser: electron beam uniformity, laser output energy, and pulsed power consistency.

The 20 cm Amplifier

The 20 cm amplifier produces a laser output of 100 Joules with an input of 0.5 Joules. The 20 cm amplifier is shown in Figure 1. A single eight stage 12 kJ Marx that charges two 3.75 Ω water insulated coaxial pulselines through two electrically identical oil transmission lines. The two coaxial lines are nominally charged to 675 kV, and are switched to their respective field emission diodes by a laser triggered, gas insulated, output switch. This single gap switch is filled with a 70% SF_6/30% Ar mixture. The trigger for both switches is provided by a 4 nsec long, 10 times diffraction limited laser beam produced by a single Nd-YAG laser (λ = 266 nm). The laser energy incident in each switch gap is 10 mJ. Routine jitter of the switch firing with this arrangement is less than ± 5 nsec. The vacuum insulator is a radial monolithic arrangement which uses external field coils to divert the main guide field lines radially outward

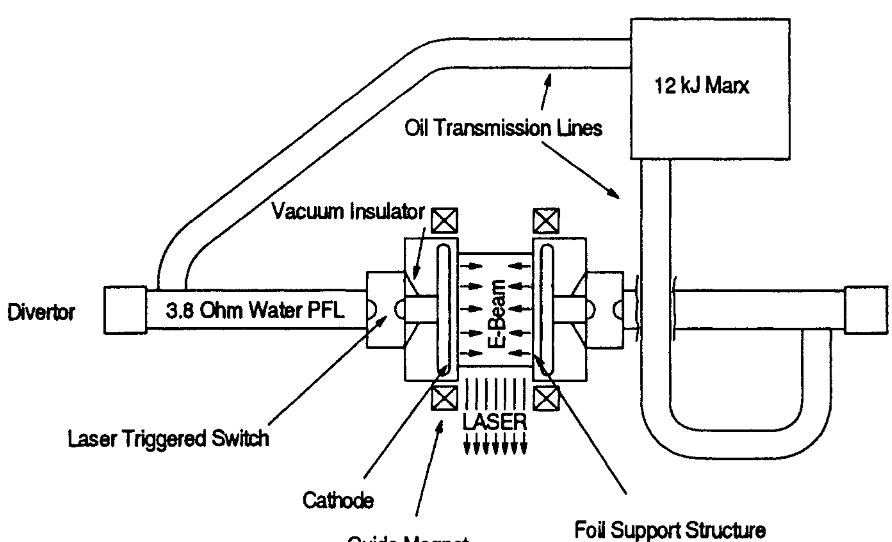

Figure 1: The Nike 20 cm amplifier

away from the insulator. We found this necessary to eliminate insulator flashover, presumably because the cusp-like geometry steers backstreaming electrons away from the insulator. The diode consists of a field emission cathode 20 cm high by 80 cm long and a .002" (50 μm) Kapton (polyimide) foil anode. The Kapton is coated with 2000 Å of copper to ensure the electric field in the A-K gap is uniform. The nominal diode voltage and current is 300 kV, 75 kA, with a pulse length of 180 nsec (FWHM). The electron beam is injected into the laser cell which is filled with a krypton-fluorine-argon mixture at pressures up to 1100 Torr. The diode is isolated from the cell with a .003" (75 μm) Kapton foil that is held with a grill-like foil support structure.

The electron beam current density in the cell is measured with a 2.3 cm diameter Faraday cup. Figure 2 shows two overlaid traces; one from the Faraday cup, the other of the current through the cathode stalk, as measured with a simple B-dot probe. This result is obtained at several other Faraday cup positions across the electron beam aperture. The close agreement between the two indicates to us that the electron beam in the cell is very uniform.

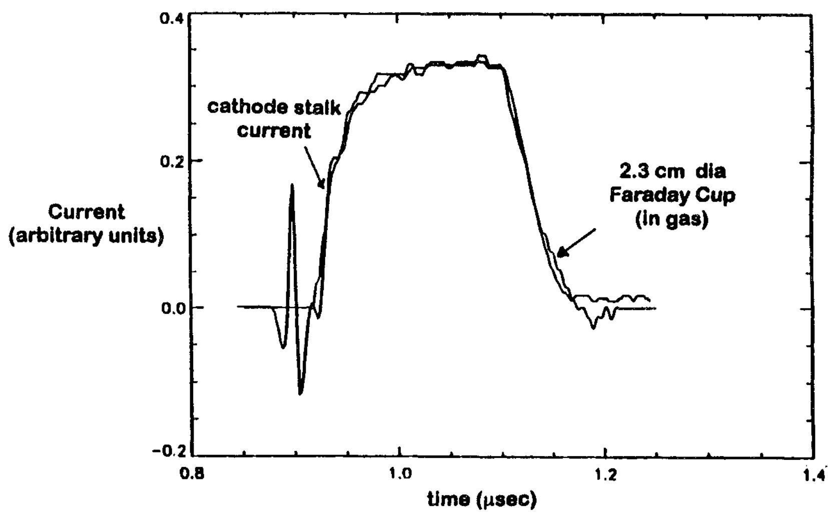

Figure 2: Overlay of the electron current in the gas and the cathode stalk current.

The laser performance of the 20 cm amplifier is shown in Figure 3, where the experimentally determined and theoretically predicted laser output energy as a function of the laser input and the electron beam pump power are plotted. Both laser input and output energies are measured with fast calorimeters. The electron beam pump power is determined by measuring the electron beam energy deposited in the gas and dividing it by the 140 nsec flat top power pulse. The deposited energy has been corrected for energy lost by radiation, amplified simulated emission [ASE] and, of course the laser beam itself, and has been referenced to the 20 cm entrance. The predictions, shown as the curves in Figure 3, are from a simple PC- based KrF kinetics model that includes all the major kinetic and optical processes[4]. As can be seen, the agreement between the two is quite good.

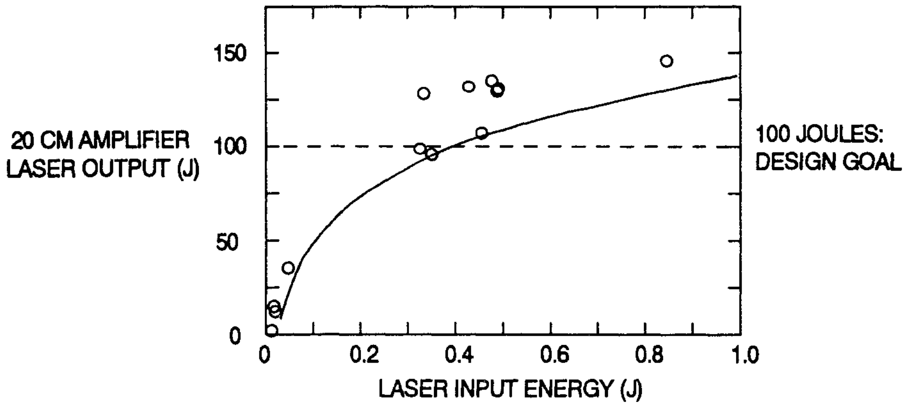

Figure 3. The laser energy output from the 20 cm amplifier. The open circles are measured data, the curves are code predictions. The dashed horizontal line is the design goal of 100 Joules laser output.

One of the salient features of the 20 cm amplifier is the efficient electron beam transmission through the diode/laser cell window support structure. Our measurements show the transmission efficiency is almost 50%, where the efficiency is defined as the total energy deposited into the cell divided by the total electrical energy transmitted through the cathode stalk. This is an uncharacteristically high figure for a device of this size.

The pulsed power for the 20 cm amplifier has proven to be quite reliable and reproducible. Figure 4 shows several overlaid current traces through the east diode. The diode current traces can be overlaid on a day to day, and even year to year, basis.

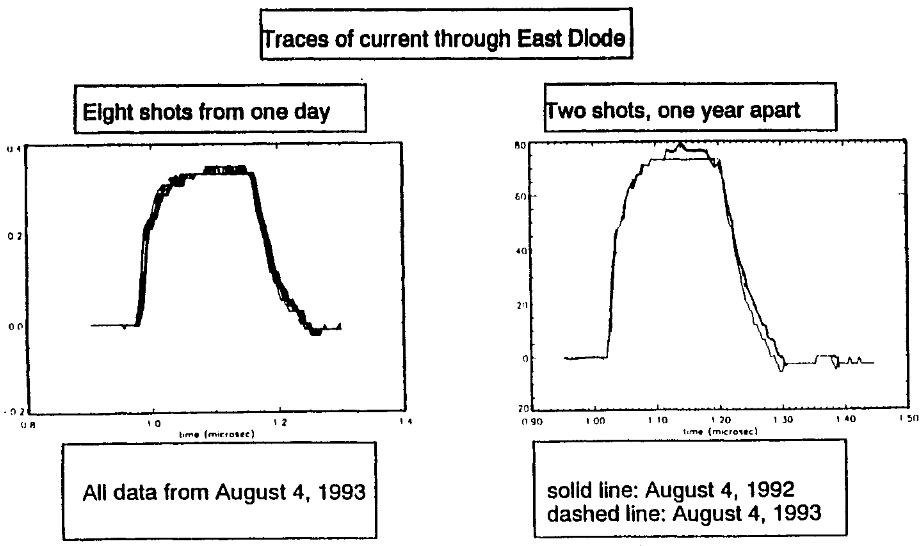

Figure 4: Overlaid current traces of the current through the east diode of the 20 cm amplifier. *Left:* Eight traces overlaid from a single day; *Right:* two traces one year apart. The currents are measured with single turn loops (B-dot probes) in the cathode stalk.

The 60 cm amplifier

The 60 cm amplifier produces 5000 Joules of laser energy in a 240 nsec pulse. The amplifier cell has a 60 cm x 60 cm aperture and is 200 cm long. A schematic of the overall layout of the 60 cm amplifier is shown in Figure 5. Unlike the 20 cm, the 60 cm uses two independent electron beam systems, which we designate as north and south. The Marx generators follow the well-proven ANTARES[5] low inductance arrangement. They have 24 half stages (i.e. 12 switches) with each half stage composed of two 2.8 μF @60 kV capacitors. Typical maximum charge voltage is 50 kV/half stage, with a stored energy of 168 kJ. Each Marx is connected to four separate oil transmission lines that contain electrically identical 2 Ω resistor/1.2 μH inductor networks. These electrically isolate the pulselines from each other in order to prevent all the lines from discharging into one if a fault develops. Each oil transmission line is connected to one of four water dielectric coaxial pulse forming lines. The oil lines vary in physical length to compensate for the 90° bends in the water pulselines, which we had to incorporate in order to fit the amplifier in the available space. While creating a few mechanical complications, the electrical effects of these bends are negligible. Both numerical simulations with a three dimensional transmission line code and simple experiments with a scale model show that the bends neither degrade the output pulse rise time nor compromise the electrical strength of the system[6]. The water pulse forming lines themselves are in two sections: a 145 nsec long, 5Ω impedance main section, followed by a 20 sec long, 4 Ω peaker section. The peaker gives an initial higher voltage increase to the leading edge of the pulse in order to reduce the voltage rise time. As oil vapor is highly absorbent at the KrF laser wavelength of 248 nm, the laser beam path has been enclosed in a sealed tunnel. The design considerations for the amplifier are described in greater detail elsewhere[7].

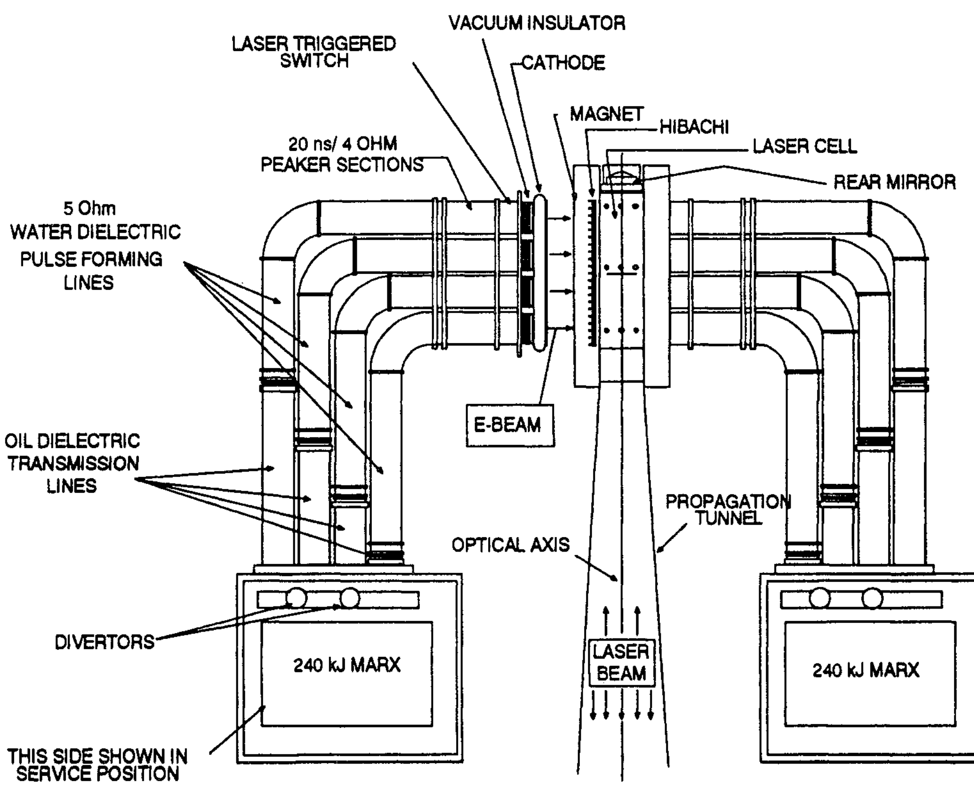

Figure 5. Overall layout of the Nike 60 cm Amplifier

Details of the output end of the 60 cm amplifier are shown in Figure 6. Each pulseline is terminated with its own output switch. The switches are SF_6 -insulated and consist of two radial nylon diaphragms that each have a single quasi-hemispherical electrode in the center. The output side of the switch is held at ground by a 100 Ω radial water resistor. Each switch is triggered with a 4 nsec laser pulse of about 11 mJ that is generated by a frequency quadrupled Nd:YAG laser (λ = 266 nm) and focused to a power density of about 5 GW/cm ^{2}. The total inductance of each switch is about 100 nH. The power is fed from each switch through an SF_6 - insulated feed section through a conventional z- stack insulator. Each of these is then fed to a common cathode. Calculations show that the insulator is operating at about 69% of breakdown of one segment[8]. The cathode shell is electropolished and the average field kept below 70 kV/cm to prevent emission of parasitic currents to the wall. The edges of the emitter are fully radiused and extend 2 cm beyond the edge of the anode aperture to help define the emission area. The emission surface itself is simply velvet cloth. However it is vital that only the highest quality velvet be used: high quality velvet has a uniform nap of sharp cut fibers and tends to ignite uniformly and very quickly. The lower quality velvet is composed of isolated tufts of rounded edge fibers, and tends to take much longer to fully ignite. The delay in ignition causes the SF_6 feed section to be overstressed, and the resulting breakdown requires a repair to the system. We now use only "Double Velvet Superfine Quality" brand[9].

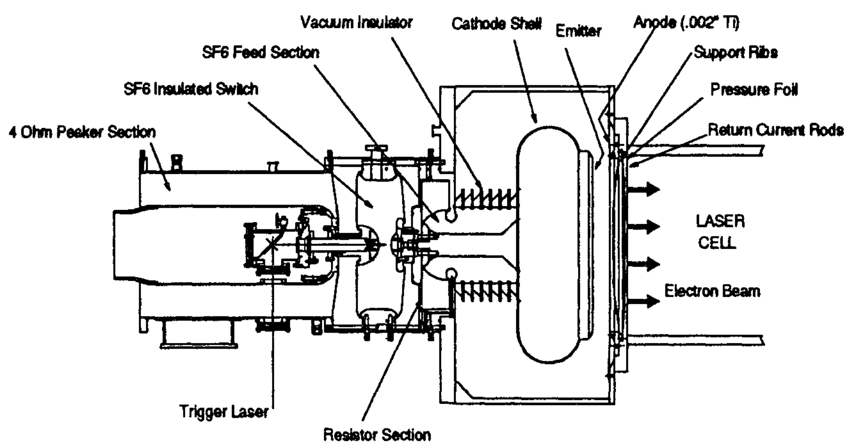

Figure 6, Output switch and e-beam diode of the 60 cm amplifier

The electron beam is passed through an anode mesh, past the foil support, and through a Kapton foil into the laser cell. The beam is guided by a 2.0 - 4.0 kG magnetic field. The foil support structure is of a new design and composed of thin, vertically mounted ribs that are made from a high strength nickel-based alloy. This structure dramatically increases the energy transmission efficiency over previous systems of this size. For example; With a .005" (.0125 cm) Kapton foil and a 42% transmitting mesh composed of woven array of .001" stainless steel wires, our energy transmission efficiency, from cathode feed to laser gas, approaches 45%. Previous systems could do no better than 25-30%[3].

The laser cell and diode boxes are a single monolithic unit constructed of stainless steel with 5 cm thick quartz windows at either end. The windows are mounted in non-parallel planes that are at an angle to the cell axis in order to prevent parasitic buildup of Amplified Stimulated Emission (ASE). The cell is designed to operate at pressures up to 2300 Torr, with an overpressure jump of up to 600 Torr. Typically the cell is filled with a mixture of 570 Torr argon, 310 Torr krypton and 3 Torr fluorine.

Figure 7 shows the output voltage and current waveforms of line #3 on the north side. These are measured with a voltage divider in the resistor section (see Figure 6), and a single turn loop (B-dot probe) in the switch, respectively. As all four lines are connected to a common cathode, the total diode current is four times that shown. We see that after the initial 75 nsec rise the power is constant to within 4% during the 240 nsec duration of laser extraction. The fast rise is directly attributable to the effect of the 4 Ohm peaker section[7], and the flat power pulse to the fact that the diode impedance drops only 20%, from 5.0 Ω to 4.0 Ω during the main pulse. This pulse shape is highly desirable for the Nike laser: The fast rise reduces ASE, and the flat main portion ensures we uniformly pump the gas during the period of laser energy extraction. The electron beam itself is well confined. Measurements with identical miniature faraday cups placed along the anode plane show the beam current density in the injected beam is ten times larger than that just outside the beam aperture, and another ten times larger than that opposite the outer edge of the cathode shell.

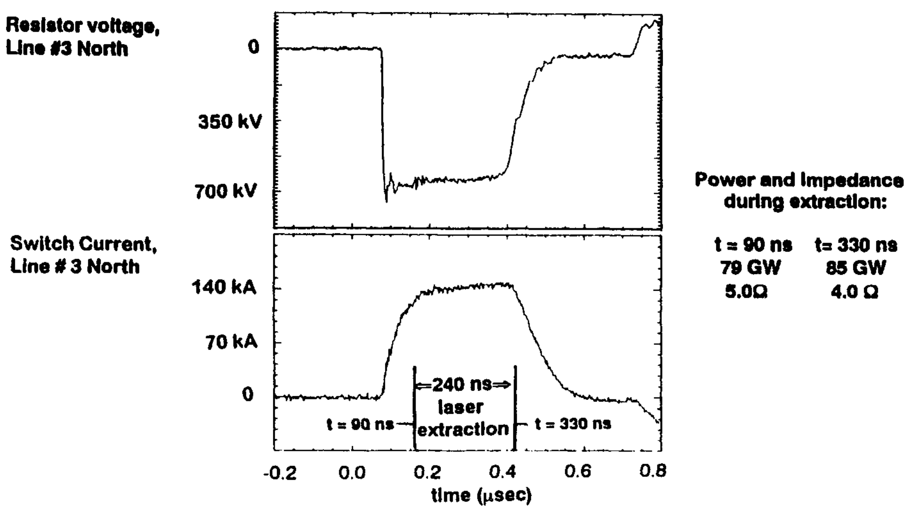

Figure 7: Resistor voltage and switch current from Line #3, north side.

The electron beam is spatially uniform inside the laser cell. Figure 8 shows measurements of the beam current in the cell at various points across the 200 cm × 60 cm electron beam aperture. The data were taken with an array of 10 cm diameter Faraday cups inside the cell located 8 cm from the pressure foil. The peak current varies by less than 10% across the aperture.

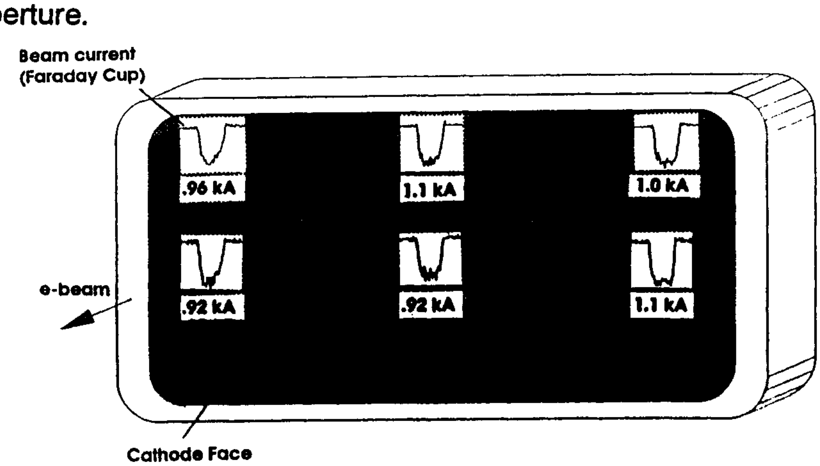

Figure 8: Beam current in the laser cell as measured with an array of Faraday Cups

Figure 9 shows the 60 cm laser output energy as a function of the energy deposited in the gas. In all cases the input laser energy from the 20 cm amplifier is 50 Joules. (As stated above, the 20 cm amplifier output is 100 Joules. However half of that is lost in the optics that relay the laser beam to the amplifier and because we "overfill" the 60 cm cell to ensure there are no unextracted regions and that the 60 cm window defines the final aperture.) The solid circles represent the measured data. The deposited energy is determined by measuring the pressure rise with a simple Baratron gauge, and assuming 10% of the deposited energy is lost to radiation, another 20% is lost to ASE, and accounts for the energy extracted by the laser beam. The laser energy from the 60 cm amplifier is determined with calorimeters. We can routinely achieve a laser output energy of 4.0 kJ. The solid curve is a compilation of calculations of the predicted laser output using our kinetics code[4]. Note that the agreement between predictions of the code and the measured laser energy is quite good. As other measurements show the energy deposited in the gas is directly proportional to the stored energy in the Marx, we can dial in whatever laser output energy we choose simply by varying the Marx charging voltage.

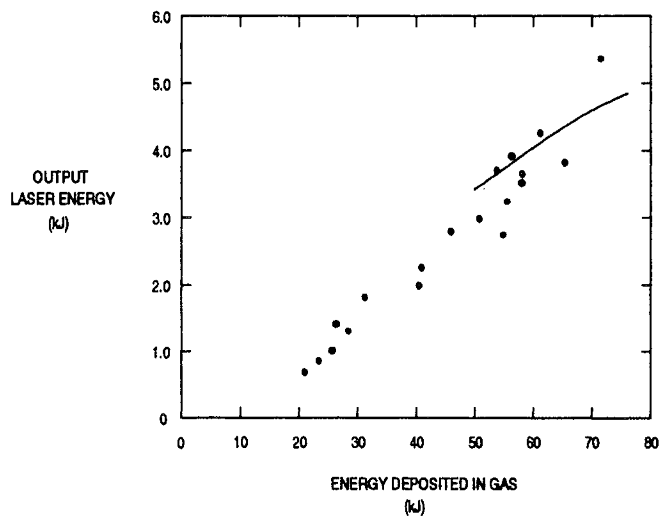

Figure 9: Plot of laser output energy as a function of electron beam energy deposited in the gas. The solid curve is the results of our kinetics calculations. Input from the 20 cm amplifier is constant at 50 J.

The 60 cm amplifier not only has the necessary laser energy, it has the beam uniformity as well. Figure 10 shows the laser beam focal profiles in the x and y direction after amplification. In this case the laser energy was 3900 Joules. These profiles correspond to an RMS deviation of 1%, a tilt of 0.8% and a peak to valley deviation of 2.3%.

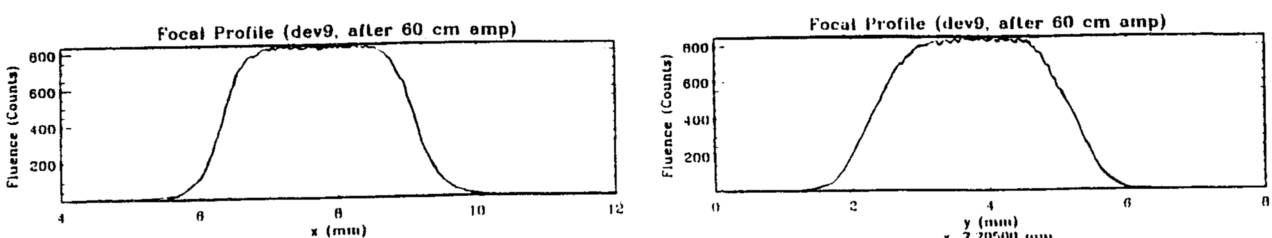

Figure 10: Laser focal profiles of the output from the 60 cm amplifier.

The two electron beam generators of the 60 cm amplifier show consistent and virtually identical performance. Figure 11 shows overlaid traces from five random shots of the current through switch #3 of each electron beam system.

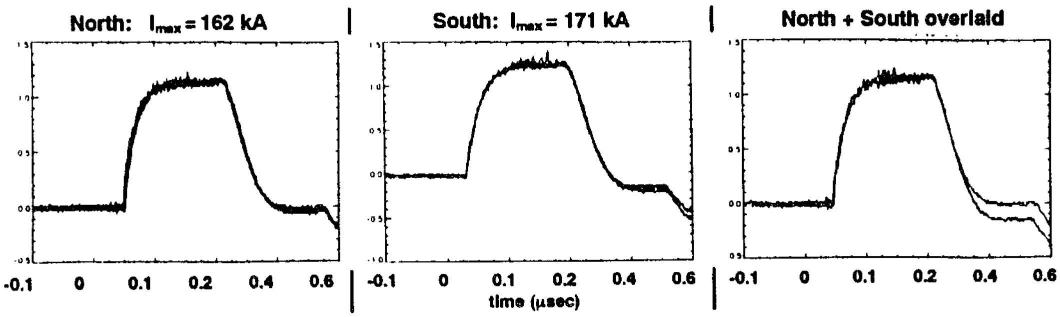

Figure 11: Current through switch #3: Left: north side, five shots overlaid. Center: south side, five shots overlaid. Right: overlaid current traces from the north and south side.

Summary

The two large electron beam-pumped amplifiers of the Nike KrF laser are complete and meet the laser requirements for electron beam uniformity, laser performance, and pulsed power consistency. The Nike laser is fully operational and target experiments were begun in May of 1995. The authors would like to acknowledge the assistance of Jim Fockler, Areg Mangassarian, Del Hardesty, Rob Morse, Jim Sawyer, Jon Peterson, John Bone, Orville Barr and Debra Gibson. This work is sponsored by the US Department of Energy.

References

1. S.E. Bodner et al, in Fourteenth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Wurzburg, Germany, 30 Sept.- 7 Oct., 1992. IAEA-CN-56, IAEA, Vienna, 1993.

2. T. Lehecka, R.H. Lehmberg, A.V. Deniz, K.A. Gerber, S. P. Obenschain, C.J. Pawley, M.S. Pronko, and C.A. Sullivan. Optics Communications 117 (1995) 485-491.

3. L.A. Rosocha and K.B. Riepe, Fusion Technology, 11 (1987) p 576.

4. M.W. McGeoch, Proceedings of the Fourth International Workshop on KrF laser Technology, Annapolis MD, May 2 -5, 1994, Paper VI-2.

5. K.B. Riepe et al, Proceedings of The Second IEEE Pulsed Power Conference, Albuquerque, N.M. June 1979, p 254.

6. J.D. Sethian and P.A. Corcoran, Rev.Sci. Instrum. 63, 1 (1992).

7. P.A. Corcoran, I.D. Smith, R.G. Altes, M.J. Christensen, B.D. Chugg, M.W. McGeoch, J.D. Sethian, S.P. Obenschain and R. L. Morse, Proceedings of The Eighth IEEE Pulsed Power Conference, San Diego, Ca, June, 1991. p. 934.

8. Ian Smith, Proceedings of the Tenth IEEE International Pulsed Power Conference, Albuquerque, NM July 10-13, 1995, paper 16-4.

9. Available from Minnesota Fabrics, Inc. 6702 Richmond Highway, Alexandria, VA.